

THERMAL MANAGEMENT SYSTEMS ROADMAP TECHNOLOGY AREA 14

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April • 2012



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 14 input: Thermal Management Systems. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.



EXECUTIVE SUMMARY

The Thermal Management Systems Technology Area (TA) cross-cuts and is an enabler for most other system-level TAs. Technology development in the Thermal Management Systems TA is centered on the development of systems with reduced mass that are capable of handling high heat loads with fine temperature control. Technologies within the Thermal Management Systems TA are organized within the three sub-areas of Cryogenic Systems, Thermal Control Systems, and Thermal Protection Systems.


Cryogenic systems require special care for numerous reasons. The primary reason is the large range of temperatures to which the cryogenic system is subjected. Secondly, the maintenance and production of cryogenic propellants requires large amounts of power which can be a driver for some systems of the spacecraft. Due to the Carnot penalty, 1 watt of heat at 20K most likely requires 150-200 W at 300K to maintain it. This dictates the need for very efficient systems so power requirements are not increased. Without effective insulation, large flow rates of gases will be vented from the tank. Fortunately, the high vacuum and low temperatures of the space environment simplifies the thermal control of cryogenics in some aspects.

The performance and efficiency of cryogenic systems will have to significantly increase in order to enable the missions being considered over the next twenty-years. New materials capable of ascent venting without performance loss or physical damage and self-healing Multi Layer Insulation (MLI) or other insulation concepts must be developed and demonstrated. Insulation systems that are built into cryogenic tank structure and the use of low-conductive composite materials will offer reductions in the combined structure and insulation mass fraction while significantly reducing cryogen boil-off losses. In addition, techniques for tailoring regolith properties to increase the thermal performance as an insulation system will have to be developed as a mission enabler for spacecraft operating on other planetary or near-Earth objects. The development of cryocoolers and other active cryogenic fluid management systems for thermal control of cryogenic propellants in space is a high priority and mission enabler for cryogenic fuel depots and long duration missions outside of low Earth orbit (LEO). Overall system goals for these systems are for reduced vibration, lower mass, and lower specific power. Also, development of large capacity liquefaction cycles (e.g., low tem-

perature radiators for pre-cooling gas, two phase flow radiators that serve as passive liquefiers) optimized for the given environment is important.

Thermal control systems maintain all vehicle surfaces and components within an appropriate temperature range throughout the many mission phases despite changing heat loads and thermal environments. Effective thermal control systems provide three basic functions to the vehicle/system design: heat acquisition, heat transport, and heat rejection while being mindful of the operational environment and spacecraft system. Technology advances for heat acquisition devices are centered on high thermal conductivity materials with a high strength-to-mass ratio and increasing the specific energy density of the systems (i.e. high thermal performance and low mass). Once waste heat has been acquired, it must be transported to a heat exchanger or radiator for reuse or ultimate rejection to space. The specific technology employed for transport is dependent on the temperature and/or heat flux and thus a wide variety of equipment and techniques can be used. The development of single loop architectures could save significant weight, reduce system complexity, and increase reliability of the thermal design of crewed systems. An additional heat transport technology requiring development is in the area of heat pipes. Loop Heat Pipes (LHP) and Capillary Pumped Loops (CPL) provide significant heat transport over long distances with low temperature drop. Thermal energy can also be stored for later use or rejection into a more favorable environment, thus significantly reducing the thermal control system mass by smoothing out the effects of peak and minimum thermal loads as well as the extreme environments. A method of coping with the periodic long-duration extremely-cold environments that will occur on planets that do not have an atmosphere is to devise a method of ameliorating the thermal environment which can significantly reduce the required mass of the thermal system design.

Thermal protection consists of materials and systems designed to protect spacecraft from extreme high temperatures and heating during all mission phases. Reusable thermal protection systems (TPS) are also key technologies for hypersonic cruise vehicles. Despite the current trend to move away from systems requiring this kind of TPS there is a national need to not only maintain this technology and its manufacturing, but also to advance the state of the art (SOA) in several areas, particularly maintainability, system size, mass,



and system robustness. Additional technology development is needed to increase the robustness and reduce the maintenance required for reusable TPS. In the area of hot structures, high temperature heat pipes hold the promise of providing high heat flux capability far in excess (5-10x) of high temperature materials. Large inflatable/flexible/deployable heat shields enable the consideration of an entirely new class of missions – flexible TPS is enabling for deployable entry systems. For many exploration missions rigid ablative materials are an enabling technology and are needed for dual-heat pulse reentries and for very high velocity entries. Advances are required to significantly lower the areal mass of TPS concepts, demonstrate extreme environment capability, high reliability, improved manufacturing consistency and lower cost, and dual-heat pulse capability. From an analytical perspective, recent efforts have revived ablation analysis capabilities but these need to be further developed to include development of material response/flow field coupling codes, integration of ablation models into standard 3-dimensional thermal modeling codes, and ground testing to generate data for code correlation and validation.

Future missions show the need for higher heat rejection, cryogenic propulsion stages, and high energy atmospheric reentry trajectories. Based on these criteria, the Thermal Management Systems TA has prioritized the following technical challenges for thermal management systems:

1. Mid-density ablator materials and systems for exo-Low Earth Orbit (LEO) missions (>11 km/s entry velocity)
2. Innovative thermal components and loop architecture
3. 20K Cryocoolers and Propellant Tank Integration
4. Low Conductivity Structures/Supports
5. Inflatable/Flexible/Deployable heat shields
6. Two-phase Heat Transfer Loops
7. Obsolescence-driven TPS materials and processes
8. Supplemental Heat Rejection Devices (SHReDs)
9. Hot structures
10. Low temperature/power cryocoolers for science applications

Successful development of the various technologies captured under the Cryogenic, Thermal Control, and Thermal Protection System ele-

ments would impact almost every figure of merit (e.g., mass, reliability, performance, etc.). Some advancements in TPS technology fall under the category of “game changing,” while others would represent significant advancements in technology currently available. Implementation of a single-loop thermal control system is a significant system simplification thereby increasing the system reliability while decreasing integration efforts for the system. Finally, 20 K cryocoolers capable of 20 W of refrigeration would offer a significant mass savings in cryogen storage through a significant reduction of cryogen boil off and would be a mission enabler for long term cryogen storage for long duration missions.

In summary, the Thermal Management Systems TA cross-cuts and is an enabler for most other system-level TA's with specific interdependencies identified with ten of the remaining fourteen TA's. The primary benefits from investment in the technologies outlined for cryogenic systems, thermal control systems, and thermal protection systems are enabling missions, reducing system mass, & increasing system reliability. Finally, the strategic roadmap for the Thermal Management Systems TA is balanced between Technology Push & Mission Pull.

Major Milestones

Cryogenic Systems

- Passive Thermal Control: Advanced Insulation (2015), Ground-to-Flight Insulation Systems (2016), Low Temp Radiators (< 90 K) (2024), ISRU Insulation Systems (2029)
- Active Thermal Control: 20 K Cryo Coolers (5 W capability) (2014), Low Power & Temp Science Instrument Coolers (2018), 20 K Cryo Coolers (20 - 40 W capability) (2020), Cryo Thermal Energy Storage (2025), Liquefaction Cycles (2030)
- Integration: Low Conductivity Struts/Tanks (2014), Deployable Cryo Tank Shields (2018)

Thermal Control

- Heat Acquisition: HX & CP (2014), TCS Fluids (2016), Adv Heat Pipes (2018)
- Heat Transfer: High Flux Cooling w/ Precise Temp Control (2016), Heat Pumps/Flow Control (2018)
- Heat Rejection & Energy Storage: Variable Coatings (2014), PCM (2014), Evaporative Cooling Technologies (2016), Ultra-lightweight/inflatable radiators (2024)
- Systems: MegaWatt TCS Mat'ls (2014), Variable Heat Rejection Radiator (2016), MegaWatt TCS Components (2020), System Integration for MegaWatt/Nuclear TCS (2029)

TPS

- Thermal Protection Systems: Rigid Ablative TPS (>11 km/s) (2016), Obsolescence-Driven TPS (2016), Reusable TPS (2016), Inflatable/Flexible/Deployable TPS (2016), In-Space TPS Repair (2018), Plume Shielding (2018), Struc. Integ. TPS (2020), Multi-Functional TPS (2026), Self-Repairing TPS (2031)

Legend:

- ★ Technology Push
- ▲ Mission Pull

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1. GENERAL OVERVIEW

1.1. Technical Approach

The Thermal Management Systems Technology Area (TA) cross-cuts and is an enabler for most other TAs. Thermal management runs the gamut from milliwatt cryogenic fluid management systems to megawatt thermal control systems for nuclear propulsion architectures; from achieving zero boil off (ZBO) for large scale in-space cryogenic fluid storage systems to protection of vehicles to aerothermodynamic heating during reentry at velocities of 11 km/s and higher; and from integration of vehicle structure and the thermal management system to insulation systems that also serve as micrometeoroid and orbital debris (MMOD) protection. Technology development in the thermal control area is centered on the development of systems with lower mass that are capable of handling high heat loads with fine temperature control. Technologies within the Thermal Management Systems TA are organized within the three sub-areas of Cryogenic Systems, Thermal Control Systems, and Thermal Protection Systems.

As long as chemical propellants are the most efficient primary propulsion systems used in space, there will be the need for cryogenic propellants. The performance of LOX/LH₂ engines surpasses other competing technologies. However, cryogenic systems require special care for numerous reasons. First is the large temperature range the system must endure. This has a wide effect on materials properties. Control or heat rejection from this temperature range require large amounts of power to produce the propellants, which can be a driver for some systems of the spacecraft. However, with proper design thermal management of cryogenic propellants may be easier in space than on Earth. Many of the cryogenic technologies detailed in this TA are driven by the mission pull of in-space cryogenic servicing needs of chemical propulsion stages in the current Human Exploration Framework Team (HEFT) Design Reference Mission (DRM) and the potential Flagship cryogenic storage and transfer mission. However, significant technology push opportunities exist as materials advances allow for development of efficient low TRL heat and energy transport processes at very low temperatures.


Material properties tend to change as they are operating in the cryogenic regime. One of the most obvious is variations in coefficient of thermal expansion between materials, which can affect rotating equipment such as pumps and com-

pressors. Many materials used in heat exchangers have large decreases in conductivity and specific heat as they approach 30K. Then there is brittleness issues limiting the classes of metals designers can work with. In addition to the material complexity are thermodynamic considerations. Due to the Carnot penalty, 1 watt of heat at 20K most likely requires 150-200 W at 300K to maintain it. This dictates the need for very efficient systems so power requirements are not increased. Finally, thermal control is important since a large quantity of super-cold fluid depends on it. Without effective insulation, large flow rates of gases will be vented from the tank. This has a major impact on mission architecture. Fortunately, the vacuum and ultra-cold sink temperature of the space environment help to simplify thermal control of cryogenics as compared to on Earth.

In its most basic form, thermal control is the maintenance of all vehicle surfaces and components within an appropriate temperature range throughout the many mission phases despite changing heat loads and thermal environments. For satellites this requires that the thermal control system must maintain all of the equipment within its operating and/or storage temperature range. Similar to the system for satellites, the thermal control system for human-rated vehicles must also maintain all of the equipment within the appropriate temperature ranges. In addition to component-level temperature maintenance, the crewed spacecraft's thermal control system must also safely maintain the internal cabin temperature within the proper temperature range to ensure both crew survivability and comfort. This section focuses on the technologies required to maintain thermal control of the vehicle within the "mid" level temperature range.

An effective thermal control system must provide three basic functions to the vehicle/system design: heat acquisition, heat transport, and heat rejection while being mindful of the operational environment and spacecraft system. The following sections discuss the critical technologies required to advance these three functions with the understanding that some of the proposed technologies overlap two or more functions and each function is dependent to some degree upon the other two.

Thermal protection consists of materials and systems designed to protect spacecraft from extreme high temperatures and heating during all mission phases. Reusable thermal protection systems (TPS) are also key technologies for hypersonic cruise vehicles. Extreme high temperatures



and heating may be due to not only aerothermodynamic heating effects but engine plume and exhaust heating effects as well.

Development of new thermal protection materials, systems, and technologies requires extensive testing using unique facilities such as arc jets and radiant heat chambers. Development of high fidelity analytical models and the associated techniques, anchored in test and flight data, with an understanding of the physics of heat transfer, stress, surface chemistry, interaction with the aerothermodynamic convective and radiative heating environments and relevant pressures and enthalpies, decomposition chemistry, and overall system performance is also required. Hence, testing and analysis, as well as a thorough characterization of material properties are assumed to be integral parts of technology development and maturation.

Finally, it should be noted that TPS technology is integral to Entry, Descent, and Landing (EDL). The entry TPS technologies identified under this TA are consistent with key technologies identified during the EDL technology road mapping process and have been fully coordinated with the EDL TA team.

1.2. Benefits

Successful development of the various technologies captured under the Cryogenic, Thermal Control, and TPS elements would impact almost every figure of merit (e.g., mass, reliability, performance, etc). Some advancements in TPS technology fall under the category of “game changing” (e.g., inflatable TPS for large mass payload delivery to Mars, heat pipes for hypersonic cruise vehicle), while others would represent significant advancements in technology currently available (e.g. lighter, cheaper, smaller, more robust, environmentally-friendly insulation materials with fewer maintenance requirements and built-in energy harvesting). A TPS fitting the previous description would save precious spacecraft weight, thereby increasing performance and payload capacity. Implementation of a single-loop thermal control system is a significant system simplification thereby increasing the system reliability while decreasing integration efforts for the system. Finally, a 20 K cryocooler capable of 20 W of refrigeration would offer a significant mass savings in cryogen storage through a significant reduction of cryogen boil off and would be a mission enabler for long term cryogen storage for long duration missions.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs


Zero boil off cryogenic storage in space has been a feature of many past and current NASA architectures, including Mars, Constellation Lunar, and current HEFT DRMs. In addition, the Space Operations Mission Directorate (SOMD) continues to help pull the state of the art in sensor cryogenic technology.

The Fundamental Aero goals as listed in the Agency Mission Planning Manifest (AMPM) include hypersonics elements that are directly supported by the TPS technologies presented here, including enabling heat pipe technology. Ablative TPS technology advancement is explicitly identified as a must for DRM 2B, and inflatable TPS development is critical for all DRMs whose ultimate end is to land a large payload on Mars. TPS Health Monitoring Systems (HMS) and integrated thermo-electric generators (TEGs) have been identified as technologies that may potentially enhance any exploration mission.

1.4. Top Technical Challenges

Future missions show the need for higher heat rejection, cryogenic propulsion stages, and high energy atmospheric reentry trajectories. Based on these criteria, the Thermal Management Systems TA has prioritized the following technical challenges for thermal management systems:

1. Mid-density Ablator Materials and Systems for Exo-Low Earth Orbit (LEO) Missions (>11 km/s Entry Velocity) – For many exploration missions, such as near-Earth asteroid and Mars missions, ablative materials are an enabling technology and are needed for dual heat pulse reentries and for very high velocity entries (i.e., >11 km/s).
2. Innovative Thermal Components and Loop Architecture – An enabling thermal technology offering significant mass and power savings and increased reliability will result from more efficient systems capable of operating over a wide range of heat loads in varying environments (for example, a 10:1 heat load range in environments ranging from 0 to 275 K). A system level approach should be taken which includes advanced fluids, advanced radiator design, and other components.
3. 20K Cryocoolers and Propellant Tank Integration – Active thermal control of cryogens in space can eliminate boil off and dramatically decrease required propellant mass for long duration space missions.



Development of low temperature cryocoolers and cryocooler to tank integration techniques are needed.

4. Low Conductivity Structures/Supports – Current propulsion stages use high conductivity aluminum as supports, leading to high heat leak. Low thermal conductance or reconfigurable supports will reduce this heat leak and minimize power requirements for active cooling systems.
5. Inflatable/Flexible/Deployable Heat Shields -- Analytical studies have shown that large heat shields provide a means to increase the down-mass to the Martian surface. Large inflatable/flexible/deployable heat shields enable the consideration of an entirely new class of missions.
6. Two-phase Heat Transfer Loops – This technology allows the transfer of small or large amounts of waste heat (typically a 1:100 ratio) over long distances, with very little temperature drop. Advanced two-phase loops allow heat load sharing thus conserving energy.
7. Obsolescence-Driven TPS Materials and Processes – This effort continues development of replacement cryoinsulation, primer, adhesive, and ablator TPS materials that are currently facing obsolescence. These four classes of materials are each subject to unique obsolescence issues that will limit their availability for future programs.
8. Supplemental Heat Rejection Devices (SHReDs) – Future technology development efforts should focus on heat rejection hardware required for transient, cyclical applications. Depending on the duration of the mission phase, this function can be accomplished using either Phase Change Material (PCM) heat exchangers or evaporative heat sinks. An evaporative heat sink utilizes a consumable fluid and future development efforts should focus on the efficient use of this consumable when an evaporator is used as a SHReD. PCM heat exchanger development, on the other hand, should focus on improving the energy storage capacity of these devices while minimizing the hardware mass. Particular attention should be focused on combining the function of PCM with radiation shielding for crew members.
9. Hot Structures – Advancements in high-temperature materials, environmental

coatings, material characterization, structural design and manufacturing processes, and life and damage assessment methods will enable the design optimization of advanced re-entry and hypersonic flight vehicles.

10. Low Temperature/Power Cryocoolers for Science Applications – Advanced low temperature cryocooler technology enables operation of detectors for scientific observation of the universe. Advances in size, efficiency and reduced vibration/interference are needed.

2. DETAILED PORTFOLIO DISCUSSION

The Thermal Management Systems TA has identified and detailed numerous technologies in the following subsections that are a mix of both Technology Push and Mission Pull. The missions that have been identified as Mission Pull candidates for technologies from this TA are identified across the top row of Figure 1 which is identified as Major Milestones.

For Cryogenic Systems, the Mission Pull opportunities are the Cryostat Demonstration and the Cryogenic Propulsion Stage which will require advanced multi-layer insulation and high-capacity 20K cryocoolers. Thermal Control Systems have identified Mission Pull opportunities for advanced phase change materials, advanced thermal control system fluids, and variable heat rejection radiators which are demanded by NEO pre-cursor robotic and Crew-to-LEO missions. Technology push opportunities for Thermal Control Systems include high temperature materials and components for megawatt systems; high flux cooling with precise temperature control; and advanced heat exchangers and lightweight radiators. Finally, for Thermal Protection Systems, the Mission Pull suite of technologies that are identified are rigid ablative TPS which will be pulled by Crew-to-LEO, Mars Sample Return, Mars pre-cursor, Hypervelocity Earth Return Demo, and Crewed NEO missions; obsolescence-driven TPS will be pulled by Crew-to-LEO; and structurally integrated TPS and multi-functional TPS will both be pulled by MMSEV and Deep Space Habitat.

The following subsections are devoted to the description of the current state of the practice, limitations of the practice, identification of the technologies to exceed these limitations, and an estimate of the current technology readiness level (TRL) and timeframe required to advance the technology to TRL 6 for the Thermal Management TA. The first-level Technical Area Breakdown Struc-

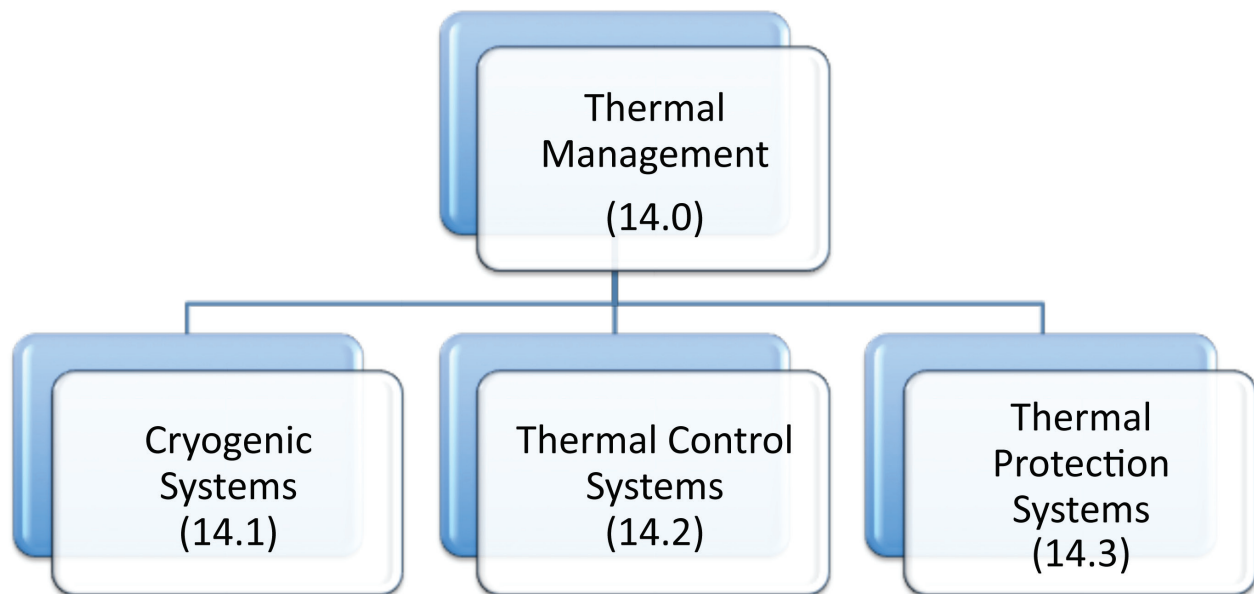


Figure 2. *First-Level Thermal Management TA TABS*

ture hierarchy is classified via the temperature regimes that thermal management systems are required to operate: Cryogenic Systems, Thermal Control Systems, and Thermal Protection Systems. This first-level hierarchy of the TABS is provided in Figure 2.

2.1. Cryogenic Systems

The first major technology area within the Thermal Management TABS is Cryogenic Systems which refers to those systems that are operating below -150°C . Cryogenic Systems is further discretized into Passive Thermal Control, Active

Thermal Control, and System Integration. The lower-tiered TABS for Cryogenic Systems is provided in Figure 3.

2.1.1. Passive Thermal Control

2.1.1.1. Large-Scale Multi-Layer Insulation (MLI)

MLI systems have been in use for in space cryogenic propulsion applications for many years but use has been limited in size and performance. Examples include the Atlas and Delta upper stages which typically have three layers of MLI and are

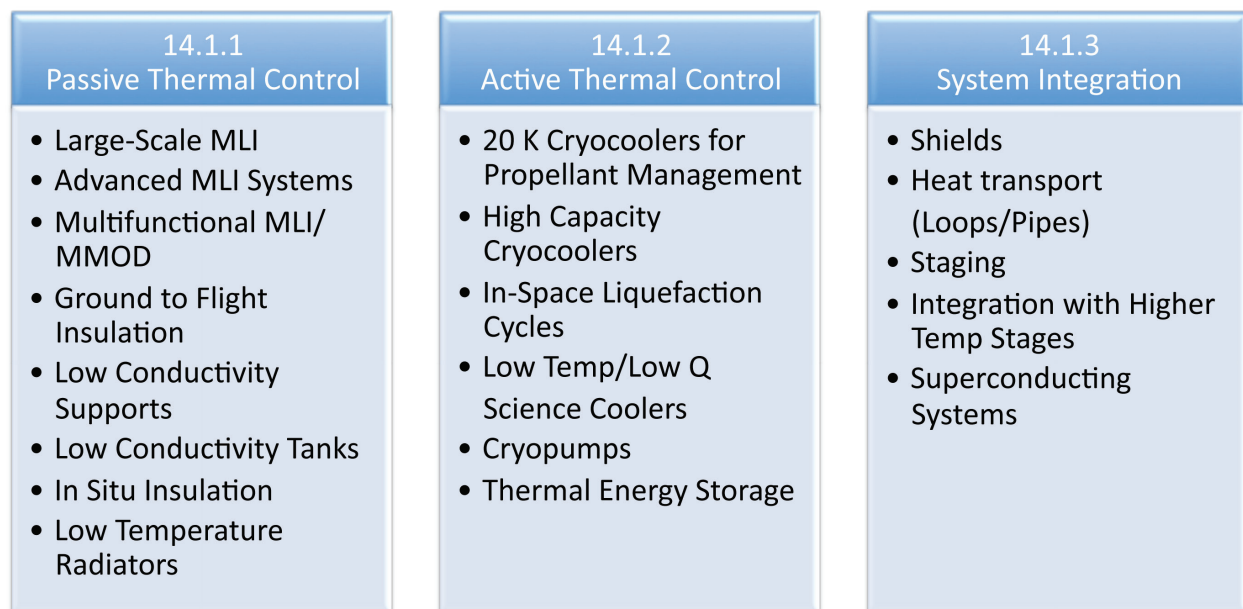



Figure 3. *Cryogenic Systems TABS*



intended for a few hours use. Evaporation rates are on the order of 2 percent per day. Future applications such as Earth departure stages require larger volumes and much longer orbital storage timelines. This will require an order of magnitude increase in thermal performance with passive evaporation rates on the order of 0.2 percent per day. Application of large number of layers and integration with vapor cooled shields on high surface area tanks must be demonstrated. Of particular interest are methods of minimizing losses at seams and penetrations and other areas of changing geometry by overlapping of layers, heat stationing blankets, or using hybrid aerogel/MLI systems. Materials capable of ascent venting without performance loss or physical damage must be developed and demonstrated. Currently, high performance large scale MLI systems for space applications is at Technology Readiness Level (TRL) 3 and successful development to TRL 6 will take 3-5 years.

2.1.1.2. Advanced MLI Systems

Current MLI concepts utilize a number of layers of radiation shielding separated by layers of low thermal conductance spacers to minimize conduction losses across the radiation layers. New MLI concepts have been proposed that eliminate the need for low conductivity layers of paper between the radiation shields. These new insulations use more rigid metallic layers separated by a system of discrete molded polymer spacers to precisely control spacing and layer density. Lower mass and higher performance are predicted benefits over current systems. The possibility also exists to expand these concepts so the outer layer is capable of supporting a soft vacuum while on Earth, compressing slightly while being supported by the spacer system. This offers large performance benefits during the ground and launch phases of the mission where typical MLI systems are not very effective. Materials development and processing and manufacturing improvements needed to bring this to TRL 6 will take approximately 3-5 years.

2.1.1.3. Multifunctional Insulation/MMOD Protection

Integration of multi-functional insulating materials into other spacecraft systems can reduce spacecraft mass and increase simplicity. For instance, MLI has shown some ability to serve as an effective MMOD protection. Analysis and optimization of MLI systems to increase this protection effect is needed. Self-healing materials that


can repair damage from handling or micrometeoroids while maintaining thermal performance should be investigated. These self healing systems are perhaps 15-20 years in the future. A more near term goal is insulation built into tank structures, such as evacuated honeycomb tank walls or aerogel filled annular tanks. Multifunctional systems that serve as cryotank insulation as well as high temperature thermal protection is an ideal long term goal. Demonstrations of these cross cutting capabilities will take approximately 8-10 years.

2.1.1.4. Ground to Flight Insulation

A high percentage of the overall heat transferred to flight tanks occurs during the ascent phase of the mission. There is as much thermal energy transfer during the ascent phase as there is during 6 days of steady state orbital operations using conventional MLI. MLI is very effective while in vacuum but not as good in soft vacuum or atmospheric conditions as other insulation methods. Cryopumping of atmospheric moisture can also damage MLI and hurt on orbit performance. Hybrid insulation schemes that are effective during ground and ascent phases while still offering optimal performance for long duration on orbit storage are needed. Foam/MLI and aerogel/MLI hybrid schemes are potential options for development. Hydrophobic materials or coatings can be considered. Deployable ground insulation panels which work during launch countdown but are then detached to minimize mass to orbit are another potential solution. While hybrid foam/MLI systems have been tested in ground chambers, aerogel/MLI and deployable insulations are at TRL 3 and will require 3-5 years of development to achieve TRL 6.

2.1.1.5. Low Conductivity Supports

Conduction heat leak across mechanical supports such as struts, skirts, and feedlines can be greater than the convection/radiation heat leak across the tank surface. Innovative methods of minimizing/eliminating that loss are needed. One mitigation is to use materials with lower thermal conductivity. Low thermal conductivity composite struts are to be used on the James Webb Space Telescope (JWST). Insulation can also offer structural support while still providing thermal performance, such as load bearing aerogels. Further enhancements can be made to intercept conduction heat leak at a higher temperature by actively cooling or vapor cooling these solid structures. Methods of integrating heat intercept stations with supports and feedlines must be proven. The op-



timal long term solution is structure that is part of the load path during ground and launch phases but disconnects on orbit. Passive orbital disconnect struts, magnetic levitation, and shape memory alloy materials are all proposed solutions for this issue. For very sensitive systems, methods of electrical power and data transmission without conductive wiring could be used. Low conductivity materials can be developed and proven within the next 2-3 years but more exotic solutions such as heat intercept or supports that are capable of disconnect may require 6-8 years of development to reach TRL 6.

2.1.1.6. Low Conductivity Tanks

Use of composite materials can minimize thermal conduction across tank walls and across tank surfaces. If conduction can be decreased so much of the hydrogen tank outer wall temperature is above 77K, then helium purging can be replaced with nitrogen. Helium is an expensive non-renewable resource and its use should be limited to applications where it is absolutely necessary. This also minimizes cryopumping inside MLI layers which could affect thermal performance. Surface treatments or nanoscale gas barriers on the inside of tanks to minimize convective heat transfer from the tank wall to the liquid are possible enhancements. Non-isotropic heat conduction materials are another solution, where heat is easily transported down the length of the tank but has much higher thermal resistance across the tank thickness. These are definite areas where materials research can push radical changes in propellant storage concepts. Composite tanks are currently being tested on the ground, but these have been designed for lower mass than corresponding aluminum tanks, not necessarily for thermal performance. Surface treatments or anisotropic material developments are probably 10 years away from TRL 6.

2.1.1.7. In Situ Insulation

This section considers the availability of local resources and environment as a part of the passive thermal control system. Technologies in this area are based on ideas such as using lunar or Martian regolith as bulk insulation materials in a manner similar to perlite on Earth. Separation of regolith components to remove high thermal conductivity metals is needed. Use of geographical features such as craters on the lunar surface or lava tubes to minimize environmental transients must be considered. Insulation schemes that are reusable and reconfigurable for secondary applications are

needed, so more durable and less fragile insulation blankets can be developed. In addition, insulation optimized for 7 Torr CO₂ atmospheres also need to be developed. There has been some small scale thermal testing of simulated lunar and Martian regolith, but research on tailoring regolith properties for thermal performance is needed. Current TRL is on the order of 2 and will require up to 10 years of development to achieve TRL 6.


2.1.1.8. Low Temperature Radiators

The effective heat sink temperature of deep space is 3K. This offers potential for a simple source of cryogenic temperature. However, due to the T⁴ nature of radiation, low temperature radiators require very large areas for any large loads. Presently, the low temperature limit is approximately 50K for LEO applications, and this is for very small loads (milliwatt scale). The JWST, which is located at L2, far away from any planetary thermal load, requires about 16 m² to radiate approximately 0.5 watts to deep space. Advances are needed including deployable systems, so they are packaged for launch and deployed on orbit with a much larger radiative area. Ideal materials are flexible for launch but are capable of being rigidized while maintaining very high emissivity. Concepts that offer large deployable radiators with integrated shielding for lunar surface systems or on orbit spacecraft are needed. Shields that are reconfigurable to minimize spacecraft orientation requirements have benefits. Elimination of parasitic heat leads to allow for lower temperature passive cooling such as those described in the low conductivity supports section also are applicable here. 50K radiators in the milliwatt range are currently TRL 9, but increasing the capacity to the watts range while decreasing the operating temperature to 20K will require approximately 8-10 years prior to reaching TRL 6.

2.1.2. Active Thermal Control

2.1.2.1. 20 K Cryocoolers for Propellant Management

Development of cryocoolers for thermal control of cryogenic propellants in space is a high priority. This technology will enable long duration storage of cryogenic propellants in orbit. Our current propulsion stage experience threshold is about 9 hours time on orbit prior to reentry, but will need to be extended to 2-3 years for some future missions. Applications include on orbit cryogenic depots, long duration Mars stages, and *in situ* resource utilization (ISRU) production on lunar or



Mars surface. There is an immediate need for the planned Cryostat demonstration mission in 2016.

For liquid hydrogen systems, higher power 20K coolers are an immediate need. The current state-of-the-art (SOA) is pulse tube refrigerators with a capacity of 1 W at 20K, with specific power in the range of 180 W/W. There is a general range of needed capacities listed below, but specific missions will have exact requirements. Initial requirements are ~5W at 20K for a Cryostat-scale ZBO system. Later stages will require 20W at 20K for larger storage volumes and possible propellant conditioning in space. Both of these applications should target a specific power of 100 W/W. Reduction in power input and heat rejection requirements is critical, as leads to mass savings in other spacecraft systems. Eventually even higher power systems will be required for liquefaction of hydrogen gas produced by ISRU. Such systems could include open cycle liquefiers, closed cycle refrigerators, or a hybrid option of the two. Overall system goals are for reduced vibration, lower mass, and lower specific power. Staging for minimal power requirements is necessary. TRL for 5W and 20W at 20 K systems is currently at 4 and development up to TRL 6 will take 2-3 years. Higher power stages for ISRU liquefaction will take an additional 3-5 years.

In addition to cryocooler systems, specific component development is needed. These components include regenerative and recuperative heat exchangers, rectifiers, and turboalternators.

Materials that have high thermal conductivity and high heat capacity at low temperatures (below 30K) are needed for low temperature Alternating Current (AC) cycle regenerative heat exchangers. Current higher temperature coolers use stainless steel or lead materials that have a dramatic decrease in heat capacity as temperatures approach 20K. Rare earth elements such as Er-Pr have better thermal properties at those temperatures but have mechanical limitations. Processing methods for rare earth elements to make regenerative screens, beads, fibers or foils in reproducible and cost effective manner need to be developed. It is important to characterize the mechanical properties and address potential lifetime issues and failure modes. Alternatives to the rare earth materials currently being used in this application should also be investigated. Currently, the TRL of low temperature regenerators is 4 and will take 3-5 years to raise this to TRL 6.

Pulse tube cryocoolers have proven to be a reliable and effective method of producing cryo-

genic refrigeration for space missions. However, pulse tube coolers have a disadvantage when distributed cooling is required. Methods of converting pulsing AC cryocoolers to enable circulation (DC flow) are sought. Of particular interest are low- temperature rectifiers so there is no need for a recuperative heat exchanger in the flow stream. Further optimization of the rectifier into the pulse tube cooler is also needed and characterizing the performance of the distribution system must be done. Current TRL is 4 and development to TRL 6 will take 3-5 years.

Effective recuperative heat exchange is a critical function for DC cycle coolers such as Joule-Thompson (JT) and Brayton cycles, as well as open cycle liquefaction systems. Current recuperators tend to be the heaviest components in space cooling systems. The current SOA is perforated plate designs. Major losses come from longitudinal conduction from warm to cold ends. Ways of maximizing conduction across the flow paths while minimizing conduction on the flow direction are needed. Anisotropic materials would be an ideal solution. These materials include heat transfer surfaces such as carbon or metallic foams that can act as fins to increase radial heat transfer and provide support for thinner walls. Microplate heat exchangers that use very thin walls and long flow paths that can be easily produced with maximum flow uniformity within the channels are also an option. Several companies are working on suitable solutions and it is estimated that higher performance options will take 3-5 years to fully develop to TRL 6.

Turboalternators provide a method of recovering the work produced by the turboexpander for increased cryocooler efficiency. The use of turbine shaft work to drive a compressor can be investigated. Microturbines with low leakage and bypass rates when using hydrogen and helium need to be developed. It is also important to increase the thermodynamic efficiency of the expansion process. Alternatives to gas bearings such as magnetic bearings should be examined. Miniature foil bearings would allow numerous start/stop cycles. Turboexpanders that can handle multiphase flow while remaining balanced and operating correctly on the bearings will be important. Some work is being done on a prototype 20K turboalternator, and this could achieve TRL 6 within 1 year. More advanced options such as magnetic bearings and integrated turbine/compressor devices will require 5-8 years for development.

2.1.2.2. High Capacity Cryocoolers

Current pulse tube cryocoolers have scaling issues when increasing the capacity beyond the current SOA. It will be important to scale up pulse tube cryocoolers so they can produce hundreds of watts of cooling at lower temperatures. Acoustic streaming phenomenon such as DC flow in dual orifice pulse tubes should be eliminated. Radial flow and turbulence issues have to be understood and controlled. Characterizing proper phase angles for larger geometries will potentially be different than for smaller coolers. Development of these systems is estimated to require 8-10 years to reach a sufficient TRL.

2.1.2.3. In Space Liquefaction Cycles

Eventual human bases on the Moon or Mars will rely on *in situ* resource utilization to produce necessary propellants and life support consumables. For propellant use, liquefaction will be required. The current SOA is large scale liquefaction and production plants on Earth. Development of large capacity liquefaction cycles that are optimized for the given environment will be important. This includes low temperature radiators for pre-cooling gas as well as potential two phase flow radiators that serve as passive liquefiers. Integration of the cooling cycle with the ISRU plant from a thermal perspective, including effective recuperator heat exchangers and high pressure electrolysis systems that serve as compressors for the liquefaction cycle. Methods of expanding isentropically with multiphase working fluids need to be investigated. Development of these liquefaction cycles will require extensive integration with ISRU systems and will require 10+ years of development.

2.1.2.4. Low T, Low Q Coolers for Science Instruments

Applications include a variety of space based science platforms including space telescopes, Earth observing systems, and a variety of instruments ranging from X-ray to infrared (IR).

Development of low power 35K, 10-6K and 2K cryocoolers is required to cool the next generation of science instruments. 35K coolers are needed for mercury cadmium telluride long wave IR detectors. 10K - 6K coolers are needed for arsenic-doped silicon detectors which operate in the IR. 2K coolers are needed as upper stage for lower temperature Adiabatic Demagnetization Refrigeration (ADR) systems for X-ray spectrometers. Advances in magnetic materials for ADR's to increase the temperature regime to include high temperature superconductors could offer alternatives to

current cryocooler systems at 20-70K. Higher density magnetic materials are needed. New paramagnetic materials are needed for ADR operation at 20mK. For all applications, cryocooler development goals included minimization of mass and specific power, and reduced vibration levels.

2.1.2.5. Cryopumps

Development of cold gas compressors and cold liquid circulating pumps with long life, variable speed operation, and very low leakage are needed for intermediate heat transport loops. Cold control valves with low heat leak are also needed. Piezoelectric materials have potential to offer lower heat leaks from actuators. Advances in compressor design using non-contact bearings such as magnetic or foil configurations will increase system reliability of these components. These technologies are important for cryogen processing and sub-cooling. Development of these systems will require 3-5 years to reach TRL 6.


2.1.2.6. Thermal Energy Storage

Advanced fluids systems that are sub-cooled or even solid that can store refrigeration energy at some times while providing thermal margin at other times so cryocooler loads can be balanced and minimized. Sufficient sub-cooling on the ground also increases the vent-free storage time in early mission phases dramatically. Advances in this area can help push rocket motor development towards densified propellants. To maximize this advantage, utilizing the heat of vaporization to absorb heat leak can be accomplished. An additional benefit of solid to liquid phase change storage systems is minimization of convective heat leak into the tank. Basic liquid sub-cooling systems can reach TRL 6 within 3-5 years but phase change systems will require 8-10 years.

2.1.3. System Integration

2.1.3.1. Shields

The use of deployable shields to eliminate radiation to storage tanks and cold instruments should be investigated. Radiation shields offer critical thermal protection for low temperature systems and are currently being baselined for the JWST. Future development will be closely related to advances in flexible materials that have low emissivity and non diffuse surfaces. Adjustable shields and louvers to control the thermal energy flow to the system are another example that is at a relatively high TRL. Actively cooled shields that intercept heat at higher temperatures will also be needed. The overall goal is to increase the effectiveness of



active cooled shields and distributed cooling systems. Use of shields for in-space propellant storage will require 3-5 years development to reach TRL 6.

2.1.3.2. Heat Transport

Integration of cryocoolers with science instruments is a critical function. Ways to transport the cooling capacity efficiently across small distances on spacecraft have to be advanced. Distributed cooling systems including Brayton and JT coolers have to be characterized. Advances in heat pipes and loop heat pipes with higher conductance in the 10K temperature range need to be achieved. Advances in heat switches and heat pipe technology are required to enable high conductance in the “on” position and low conductance when “off”, especially for temperatures below 10K. The ultimate goal is thermal superconductivity, and successful development can push the incorporation of cryogenic systems into the mainstream energy transport sector. Surface treatments for materials may allow for lower thermal contact resistance. Evolutionary advances in heat transport systems are possible over the next 3-5 years but revolutionary advances such as surface treatments and integrated switch/pipe systems may require 6-8 years to reach TRL6.

2.1.3.3. Staging

Integration of 20K coolers will use cryocooler staging at higher temperatures. To optimize the system for minimal power and mass, staging of the coolers and heat intercept at higher temperatures is needed. Methods of higher temperature shielding and integration into passive thermal control scheme are needed. Heat intercept across solid interfaces such as struts, skirts, and feedlines should be developed. Heat transport systems such as circulation pumps, AC/DC flow rectifiers, and DC cryocooler flow control are needed to effectively transport cooling loads across distances of meters and areas of tens of square meters. Multi-stage 20K coolers with high temperature heat intercept will require 2-4 years of development to reach TRL 6.

2.1.3.4. Integration with High Temperature Systems

Cryocooler systems that reject waste heat to warmer temperature environmental control and life support system (ECLSS) cooling loops as opposed to dedicated radiators at higher temperatures should be investigated. This allows for a lower ΔT between the cold and warm sides of the cryo-

cooler system which will increase efficiency. Methods of removing waste heat from coolers such as integrated heat exchangers and liquid cooled compressors should be studied. Heat exchangers with more than two working fluids should also be developed for integrated heat transport. These systems are used extensively in ground applications and transition to space systems should be relatively straightforward and take 2-3 years to reach TRL 6.

2.1.3.5. Superconducting Systems

Eventual power transmission applications will benefit from using superconducting tapes to eliminate electrical resistance heating, both reducing waste heat as well as reducing overall power required. Such systems could be also incorporated into motor windings for a superconducting motor and possible for low voltage instrumentation to eliminate conduction losses on extra sensitive science packages. Higher temperature superconducting magnets have projected applications in science missions. Development of active and passive cryogenic systems for both low temperature and high temperature superconducting applications is needed. There are opportunities for technology push in this area.

2.2. Thermal Control Systems (Near Room Temperature)

The next major technology area within the Thermal Management TABS is Thermal Control Systems which refers to those systems that are operating between -150 °C and 500 °C. Thermal Control Systems is further discretized into Heat Acquisition, Heat Transfer, and Heat Rejection and Energy Storage. The lower-tiered TABS for Thermal Control Systems is provided in Figure 4.

2.2.1. Heat Acquisition

Heat acquisition is the process of acquiring excess thermal energy from various components including power, electronics, avionics, computers, and metabolic loads from crewmembers. Heat acquisition is typically accomplished using a myriad of hardware components: mainly, but not limited to, coldplates, air/liquid heat exchangers, and liquid/liquid heat exchangers. Heaters are also considered a component of heat acquisition and are generally used to address temperature differences created by the environment or differences in heat generation between components or areas of the spacecraft.

2.2.1.1. Coldplates and Heat Exchangers

Heat exchangers and coldplates are presently

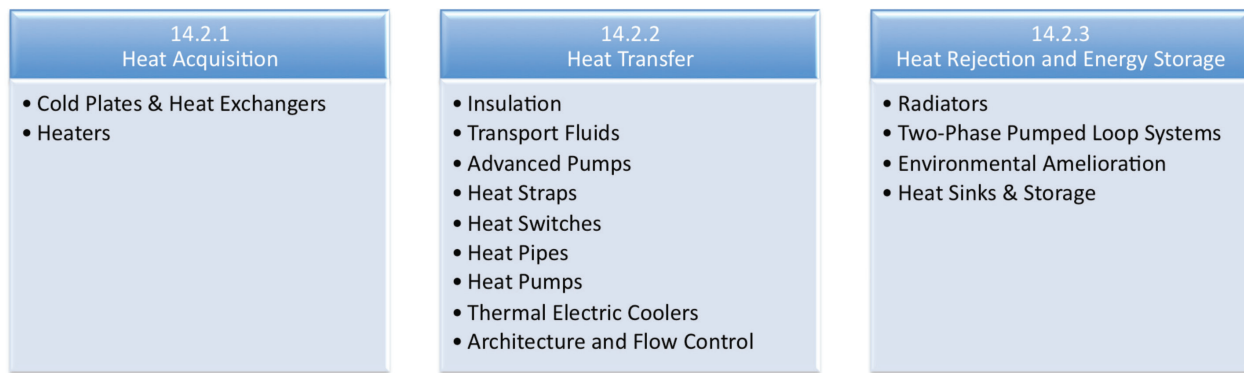


Figure 4. *Thermal Control System TABS*

made of metals such as aluminum and stainless steel. Both heat exchangers and coldplates include heat transfer fins which are required to enhance the unit's heat exchanger efficiency. Higher efficiency/lower mass designs can be realized through the use of micro-channel fabrication techniques or the use of composite materials. Composite materials are desirable for the fabrication of heat exchangers due to their potentially high thermal conductivity and high strength-to-mass ratio (especially composites enhanced by nanotechnology). Micro-channel fabrication techniques can also be used to reduce the fin spacing by an order of magnitude increasing the thermal performance while also dramatically reducing the hardware mass and volume. Both concepts are at a TRL of 2-3, but can be advanced to TRL 6 in 3-5 years. The materials development work should be coordinated with the Materials, Structural & Mechanical Systems, and Manufacturing (TA12) TA, but requirements and testing should be led by the Thermal Management TA. Improvements in cooling and dehumidification of airflow in condensing heat exchangers are the responsibility of the Human Health, Life Support and Habitation Systems (TA06) TA.

2.2.1.2. Heaters

An efficiently designed spacecraft would use available waste energy to provide heat where required, using as few heaters as possible. While advanced two-phase loops can provide this function, engineering compromises require that heaters be used to address the cold component temperatures caused by the environment and to provide condensation control for internal cabin surfaces. Heaters consume power and frequently add to the overall heat load for the rejection system. The reliability of heaters and their associated control circuits are low enough that generally at least one redundant circuit is required. NASA's planned level


of investment is very low in developing highly reliable heat generation devices. The SOA has not changed much over the past 50 years. The major challenges include increasing reliability and minimizing overall waste heat generation. New materials and heater concepts to increase iso-thermality, increase control reliability, and minimize burnout or thermal fatigue are critical. Improved sensors and thermostats are desired to allow more precise temperature control and better redundancy. These devices are at TRL 1-3 and could be advanced to TRL 6 in 7-10 years.

2.2.2. Heat Transfer

Once waste heat has been acquired, it must be transported to a heat exchanger or radiator for reuse or ultimate rejection to space. The specific technology employed for transport is dependent on the temperature and/or heat flux and thus a wide variety of equipment and techniques can be used. In some cases, heat transfer is not desired or must be tightly controlled and technologies to limit or prevent heat transfer are also critical.

2.2.2.1. Insulation

Thermal transport of waste or to-be-reused heat must first be controlled within a defined path. Insulation is critical to this function. This is typically accomplished via MLI, specialized thermal coatings such as gold or various paints on a spacecraft body, or aerogels or other solids in situations where MLI or coatings are ineffective such as on balloons or planetary surfaces. Room temperature MLI technology is well established. One area still at a lower TRL (4-5) is with insulation intended for very high temperature environments (e.g., aerogels or special MLI), such as for missions going close to the Sun or landing on Venus. Planetary environments such as Venus present a special case since there is both a dense atmosphere and very high temperature. In this situation MLI is



useless and advanced high temperature/high performance insulations will be needed. Additionally, high performance insulation systems, which are more easily fabricated than traditional MLI systems, are desired for both hot and cold environments. Both of these technologies could be advanced to TRL 6-8 in 3-5 years.

2.2.2.2. Transport Fluids

For robotic spacecraft where human life support is not an issue, the most common heat transport fluids are ammonia, fluorocarbons, and propylene for room temperature applications with methane, ethane, nitrogen, or oxygen employed for cryogenic applications (dependent upon specific temperature). Such fluids are used for both single-phase applications (typically via the mechanical pumping of a liquid) or for two-phase applications (transported either mechanically or by capillary forces).

For human tended spacecraft, it is desirable to develop technologies that enable single-loop thermal control system architectures rather than the current state-of-art, which is an internal/external two-loop architecture. The single-loop architecture would have benefits of improved reliability, system simplicity, and significant mass savings. Typically, thermal control systems, including the vehicle's radiator, are sized for the maximum continuous heat load in the longest sustainable thermal environment. This design approach results in a fairly large radiator surface area. Unless some sort of protection is provided, the heat transfer fluid will need to have a relatively low freeze temperature must be incorporated into the design to avoid freezing the fluid during cold and low-load mission phases. Unfortunately, most of the fluids that have low freeze temperatures (fluorocarbons, ammonia, etc.) are also toxic to crew members and cannot be used inside the pressurized spacecraft volume for fear of an inadvertent system leak. As a result, two-loop thermal control system architectures are typically designed to use low freeze point temperatures in the external loop and a more benign fluid in an internal loop which is connected via an inter-loop heat exchanger which adds substantial mass to the system.

Single loop architectures could save significant weight. They could be enabled either by developing advanced fluids and/or developing variable heat rejection radiator technologies. The development of advanced fluids should be focused on low toxicity while depressing the freeze temperature and ensuring that the advanced fluid has im-

proved thermophysical properties. Advanced thermal fluids are currently at TRL 2-3 and could be advanced to 6-7 in 3-5 years.

2.2.2.3. Advanced Pumps

Mechanical pumps are often used to move fluid through a thermal control system. Advanced technologies such as piezoelectric pumps and/or electrohydrodynamic pumps offer very high pumping efficiencies (>90%), longevity and negligible vibration. Reliable check valves would allow the inclusion of a redundant pump, if needed. Current TRL for these technologies is around 3-4 and could be advanced in 5 years to TRL 6.

2.2.2.4. Heat Straps

Occasionally it is necessary to passively transport heat from one specific location to another within the spacecraft itself or to spread the heat load across a wider area. In these situations it is often convenient to use a heat strap, which is a mature technology that typically uses higher mass materials such as copper and aluminum. Emerging technologies using ultra high conductivity carbon fibers, artificial diamond films, carbon nanotubes, boron nitride nanotubes, (now at TRL 2-4) or other such materials promise lower mass/thermal conductivity and could be developed to TRL 6 in 3-5 years.

2.2.2.5. Heat Switches

Heat switches are often employed with heat straps, or at connection points between equipment. These devices allow, or prevent, a thermally conductive link. Heat switches may be designed to be purely passive, by opening or closing at specific pre-selected temperatures, or they may be under active command. Technology improvements are possible and the goals are typically higher thermal conductivity with lower mass for the device, and/or higher ratios of conductance in the "on" and "off" conditions. Desired performance of heat switches is currently at a TRL of 2-3 and could be advanced to TRL 6 in 3-5 years.

2.2.2.6. Heat Pipes

The most efficient heat transport phenomenon involves convective flow associated with a change in phase of the heat transport fluid. The fluid is generally contained within a tube, or separate tubes for the liquid and vapor sides, and is continuously recycled. The fluid can be circulated either by a mechanical pump or by the capillary forces generated by a wick. Two-phase loops driven by capillary forces have the advantage of not requiring an external force, such as a mechanical pump,



to circulate the fluid.

Heat pipes are the most common capillary-driven device used in spacecraft today. A traditional heat pipe includes a hollow tube, sealed on both ends, with an interior wick and a circulating fluid. Heat pipes can transport up to hundreds of watts for several meters, at negligible temperature drop, along the length of the pipe. Heat pipes are a well-developed technology, TRL 8-9. A variety of heat pipes for cryogenic and high temperature applications have also been flown (TRL 6-9). These tend to be specialty applications and require unique designs, but the basic technology is established.

Another type of capillary based, two-phase heat transport technology involves the use of a loop where there are separate liquid and vapor lines and the wick is located only at the evaporator. Such loops are termed Loop Heat Pipes (LHP) and Capillary Pumped Loops (CPL). Loops have been built which can transport 20+ kW over a ten meter length. Conversely, smaller loops have been built that transport only a few watts to several hundred watts. These technologies offer significant heat transport over long distances with low temperature drop, are inherently self regulating, need no mechanical pump, and can last indefinitely. They are capable of very tight thermal control (i.e. ± 0.1 °C). All of these advantages are very important for scientific spacecraft that have instruments in need of precise thermal control. Existing LHPs and CPLs have only one evaporator and one condenser/radiator. Hence, an important advancement would be the development of LHPs with multiple evaporators and condensers, a technology that is currently TRL 5. A flight experiment would raise the TRL to 6-7 within 2-3 years.

Better analytical models of two-phase loops are also needed. Current models are functional, predict transients reasonably well, and are useful for design purposes, but more complete models with zero-G validated correlations are desired. This is particularly true for systems with multiple evaporators and condensers. The current TRL of 5/6 could be raised to 7/9 within 4 years.

2.2.2.7. Heat Pumps

Heat pumps have been employed for ground applications for many decades and are a relatively mature technology. Earth-based heat pump technology is not directly applicable to the rigors of the space environment. Although ground-based designs that are not reliant on gravity for elements of heat pump operation (e.g., lubricant manage-

ment, contaminant control, phase separation, etc.) are in use, intermittent operation in micro-gravity and in severe environments, such as hard vacuum, radiation, and extreme temperatures, are real concerns. Exceptionally long life, low mass, high efficiency, and operating with high temperature lifts (50 °C or more) are key improvements for space-based heat pump technology.

Depending upon the application, it may be possible to make productive use of the local environment to improve the operation of a heat pump based system. For example, in a lunar or other planetary application it may be most efficient to drive the heat pump compressor with a photovoltaic system sized such that it provides 100% of the compressor power without the use of heavy and expensive batteries. System level TRL is 4-5 and could be developed to 6-7 in 5-10 years.

2.2.2.8. Thermal Electric Coolers (TECs)


There are special situations where precise, but very localized thermal control is needed, and cold biasing with bump-up heaters is impractical. Examples include spot cooling of electronics or sensors and tight control of laser diodes. In such situations it is possible to use thermoelectric devices based on the Peltier effect. Typical applications are at a higher TRL; however it is currently a major challenge to operate TECs below 150 K. The TRL for the low temperature applications is currently at 2-3 and could be developed to TRL 6 in 5 years.

2.2.2.9. Architecture and Flow Control

Current system architectures and available fluids can result in severe limitations on system operations. The current SOA two-loop system with a regenerator bypass temperature control can operate at low heat loads in cold environments, but its operational heat load/environment envelope is still limited. Systems with wide operating envelopes that have few, if any, operating restrictions must be developed for future missions. This will require innovative system architectures and/or sophisticated control schemes. Analytical models to support such system level design and trade-off studies are also needed. The TRL for advanced architectures is very low, but could be developed to TRL 6 in 5 years.

2.2.3. Heat Rejection and Energy Storage

Heat rejection is accomplished using radiators, evaporators, and/or sublimators. Thermal energy can also be stored (either as latent heat in a phase change material or through sensible heating of a



large mass) for later use or rejection into a more favorable environment, thus significantly reducing the thermal control system mass by smoothing out the effects of peak and minimum thermal loads as well as the extreme environments.

2.2.3.1. Radiators

Radiator advancement is perhaps the most critical thermal technology development for future spacecraft and space-based systems. Since radiators contribute a substantial portion of the thermal control system mass. For example, the Altair (Lunar Lander) vehicle radiator design represents 40% of the thermal system mass. Radiators can be subdivided into two categories; the first is for rejection at temperatures below 350 K and the second is for nuclear or high power systems at temperatures around 500 K. Technology development efforts in the low temperature category should focus on heat rejection variability, advanced coatings, and mass reduction. Technology development for high temperature radiators should focus on advanced coatings and compatibility with liquid metals or other exotic heat transfer fluids.

Radiators are typically sized to reject heat during the worst case combination of peak heat load and least favorable environment. As mentioned earlier, for crewed spacecraft, this design often results in a two-loop thermal control architecture. The two-loop architecture can be replaced by a lower mass single-loop architecture by either developing advanced fluids and/or developing variable heat rejection radiator technologies. A variable heat rejection radiator must be capable of varying its effective heat transfer coefficient with the environment depending on the given mission phase. This variability could be accomplished by actively changing the radiator's infrared emissivity (e.g., a variable emissivity coating), draining the radiator fluid, changing the radiator surface area with covers, or stagnating/freezing the fluid inside the radiator in a predictable fashion. These technologies are at a TRL 2-4 and could be developed to TRL 6 in 5-7 years. Hence, there are multiple paths towards a technical solution to a significant challenge, and these involve interlinking push and pull technologies.

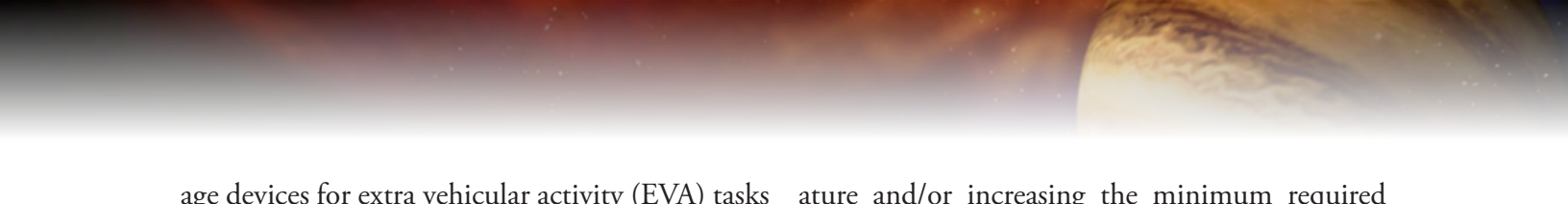
Thermal coatings are critical for moderate temperature radiator surfaces, and a wide variety of specialty coatings have been developed over the past 50 years. These coatings typically have an absorptivity to emissivity ratio (α/ϵ) of approximately 0.1. Reducing the ratio to near zero would allow effective heat rejection in full sun, which may

allow a substantial reduction in mass by reducing radiator area. A successful coating will be insensitive to the effects of environmental degradation or build up of contamination. Exactly what those degradation mechanisms are depends on the environment, but the degradation will probably be centered on those components directly exposed, such as radiators and thermal protection layers.

For example, the Hubble Space Telescope multi-layer insulation underwent dramatic degradation due to the combined effects of radiation and thermal cycling as it traveled in and out of Earth's shadow. As another example, when dust got on the Apollo lunar roving vehicle (LRV), the result was that the batteries did not cool down between EVAs. In all three LRVs (Apollo 15, 16, and 17) the batteries were run at higher temperatures than specified for most of the third EVA. In addition to dust effects, there may be atmospheric chemistry interactions with exposed surfaces. Perhaps the extreme example is Venus with its high temperature, high pressure, and acidic atmosphere. Passive (e.g., "Lotus Coating") or active techniques for cleaning radiator coatings are also being pursued, currently at TRL 3-5, and could be matured to TRL 6-8 within a few years. Prototype versions of variable emittance coatings have been flown on ST-5 spacecraft, but additional development is necessary to achieve a dynamic change of emittance of at least 4:1 and survive in a space environment for several years. There are continuing efforts to gradually improve the coating properties, but substantial decreases in α/ϵ (throughout the entire mission) are critical to next generation spacecraft.

Specialized thermal control systems will be required for nuclear or other high power spacecraft. The roadmap for nuclear power for spacecraft is addressed by the Space Power and Energy Storage Team (TA3), but the key thermal components required include high temperature liquid metal coolants with high thermal conductivity and large, multi-megawatt deployable radiators. Radiator surfaces will be required to reject heat at high temperatures (~500K). Current SOA does not exist for high temperature radiator coatings with acceptable longevity and emissivity. This will be critical to a Rankine-cycle thermal nuclear power system. Close coordination with TA3 will be required. The current TRL is at 1-2 and could be developed to TRL 6 in 7-10 years. In addition to the hardware, analytical models for high temperature systems are needed.

Finally, lightweight radiators or thermal stor-



age devices for extra vehicular activity (EVA) tasks must be developed for extended missions on extraterrestrial surfaces. Current SOA involves the use of sublimators which consumes significant mass. Compact specialized radiators or thermal storage devices could significantly reduce the consumables required for EVA. The goal is to develop a non-venting, closed-loop heat rejection system with no consumables for EVA missions. The current TRL is 2-3 and could be advanced to TRL 6 in 3-5 years.

2.2.3.2. Two-Phase Pumped Loop Systems

The benefits of two-phase systems are principally realized in phase change heat transfer where a significant amount of heat is transferred to a relatively small amount of fluid through the latent heat of vaporization. This is approximately a two order of magnitude improvement in heat transferred per unit of system mass. Two-phase systems give the additional flexibility of maintaining near-isothermal conditions in critical locations over a wide range of flow rates.

Two-phase heat transport systems, such as Loop Heat Pipes, have been used successfully in the space environment but have been limited to small heat load applications (less than 1 kW) that require the isothermal advantages. The advantages for large heat load systems, such as those requiring the use of Rankine cycle power system, have yet to be designed and tested. Furthermore, we still lack a fundamental understanding of the mechanisms involved in pool and flow boiling and condensation in partial or microgravity environments. Results from upcoming experiments on the International Space Station (ISS) will provide a TRL of 2-3 and then should be applied to a larger scale thermal control system (TCS) to develop TRL 6 in 10-15 years. Development of microgravity separators is also required. Other techniques such as the imposition of electric and acoustic fields and forced flow on the bubble nucleation and vapor bubble removal should be examined to control film dry out increasing heat transfer.

2.2.3.3. Environmental Amelioration

A method of coping with the periodic long duration extremely cold environments that will occur on planets that do not have an atmosphere is to devise a method of ameliorating the thermal environment. By trapping heat during the warm periods and giving it up slowly during the cold periods (much as a desert solar house rock-wall does), environmental amelioration can raise the minimum sink temperature, increasing the radiator temper-


ature and/or increasing the minimum required heat load to avoid radiator freezing. The specific process that must be developed is the technique to store energy into modified lunar regolith and then retrieve the energy. Initial modeling efforts require testing in appropriate environments (such as a full vacuum). The TRL for this technology is currently at a 2-3 and could be advanced to a TRL 6 within 2-3 years.

2.2.3.4. Heat Sinks and Storage

Significant technology development is required for transient, cyclical applications. These scenarios can occur when the thermal environment is varying in a cyclical fashion such as those occurring during a planetary orbit. Another cyclical application is when the spacecraft's heat rejection requirement is varying throughout a particular mission phase. The hardware used to accomplish this specific heat rejection function is commonly referred to as SHReDs. This name is used because these devices are used to supplement another device such as a radiator.

There are two primary types of hardware that can be used as a SHReD. The first, which requires a consumable fluid such as water, is an evaporative heat sink. This device rejects energy by evaporating a fluid and venting the consumable to the ambient environment. The second type is a supplemental, regenerable heat rejection device, which has the benefit of not requiring a consumable and is therefore more suitable for long mission durations. One such device is a PCM heat sink.

The mass of PCM required for a given application is inversely related to the material's heat of fusion and the time of operation. Traditional PCM heat exchangers use paraffin as the PCM. However, these materials tend to have lower heats of fusion leading to relatively heavy PCM heat exchangers. Water has a heat of fusion approximately 70 percent higher than a typical PCM with the appropriate control (melt) temperature but it has unique challenges associated with its use. Unlike most fluids, water expands significantly when it freezes, which results in unique structural design challenges. A concentrated technology development effort should be performed to make the use of water as the PCM a viable option for future heat exchangers. Water has another advantage because it is a very good material for radiation shielding. Developing a thin water shield around crew living space for exo-LEO missions and using it as a combined SHReD and radiation shield should be a high priority. TRL for water based sys-



tems is currently at 3 and could be developed to TRL 6 in 3-5 years.

Sublimators have traditionally been used for steady state heat rejection applications. However, previous test programs have shown that the overall sublimator feedwater efficiency is quite low when used as a supplemental heat rejection device. This is because of start-up and shutdown inefficiencies. In addition, many sublimators have a minimum heat load requirement due to concerns about hardware failure caused by freezing within the feedwater reservoir. This minimum applied heat load can lead to additional inefficiencies because it would result in consumable use even when evaporative cooling is not truly required. In addition to developing sublimators capable of performing supplemental heat rejection, a concerted effort should be performed to develop evaporative heat sinks capable of operating in a wide range of external pressures (post-landing terrestrial cooling, Venus or Martian environments, etc.). Indeed, along with advanced high temperature insulation, sublimators will be needed to extend operational times for a Venus Lander. Ensuring zero carryover would allow the use of back pressure control valves for temperature control. Sublimators and evaporators for this use are currently at TRL 3 and could be advanced to TRL 6 in 3-4 years.

2.3. Thermal Protection Systems (TPS)

The final technology area within the Thermal Management TABS is Thermal Protection Systems which refers to those systems that are operating between above 500 °C. Thermal Protection Systems is further discretized into Entry/Ascent TPS, Plume Shielding, and Sensor Systems and Measurement Technologies. The lower-tiered TABS for Thermal Protection Systems is provided in Figure 5.

2.3.1. Ascent/Entry TPS

2.3.1.1. Reusable TPS

With the retirement of the Shuttle Orbiter, the primary user for reusable TPS, which includes Carbon/Carbon hot structures (up to 1650 °C), tiles (up to 1260 °C), and fibrous insulation blankets (820 °C), will be gone. Despite the current trend to move away from systems requiring this kind of TPS there is a national need to not only maintain this technology and its manufacturing, but also to take this opportunity to advance the SOA in several areas, particularly maintainability, system size, mass, and system robustness. Waterproofing agents for tiles, for example, are no lon-

ger being manufactured, however future nanostructured films hold promise (see TA10 Section 3.2.1.3, 7 years to technology maturity). Therefore, there is a need to maintain the present reusable TPS design and manufacturing capability for use with future spacecraft. Additional technology development is needed to increase the robustness and reduce the maintenance required for reusable TPS. For example, the RTV breaks down at 340 °C, but higher temperature adhesives (new compounds, or those benefiting from nano-fillers [see TA10 Section 3.2.1.4]) would greatly benefit TPS designers in reducing the insulation needed to reduce bondline temperatures. Furthermore, nanostructured materials (see TA10 Section 3.2.1.2) promise to greatly increase the damage tolerance of composites (5-10 years), and potentially large increases in ceramics (as much as a factor of 1000 in 10-20 years). This would directly benefit commercial crew transportation vehicles, some of which are envisioned to rely on reusable TPS. This effort should also include development of thermal barriers, seals, and gap fillers that are usually required between segments (tiles or panels) and the development of waterproofing agents. Reusable TPS provides benefit not only during ascent, but also contributes to the spacecraft's overall on-orbit heat balance and serves as entry TPS as well. Advanced Reusable TPS may take many forms (all of which require material development and characterization) including tiles, blankets, refractory composite/refractory metallic structures, UHTCs, embedded PCMs, coatings, nanostructured materials, and heat pipes. Of these TPS technologies CMC fabrication technology development stands out as a priority as the US has fallen far behind several other countries in this both promising and critical area. Nanostructured materials could incorporate radiation and MMOD protection as well as tailoring thermophysical properties with values in excess of current SOA. High temperature heat pipes hold the promise of providing high heat flux capability far in excess (5-10x) over high temperature materials with the benefit of being light weight and a passive design. Also included in this category are hot structures, which may include refractory composites (Carbon/Carbon (C/C), Carbon/Silicon Carbide (C/SiC)), refractory metallics (Inconel, NiTiAl and Gamma TiAl systems), and the associated attachment hardware and insulation systems. High TRL (4-5) items may be developed in 2-3 years of effort. Lower TRL (2-3) items may require 4-5 years of development time.

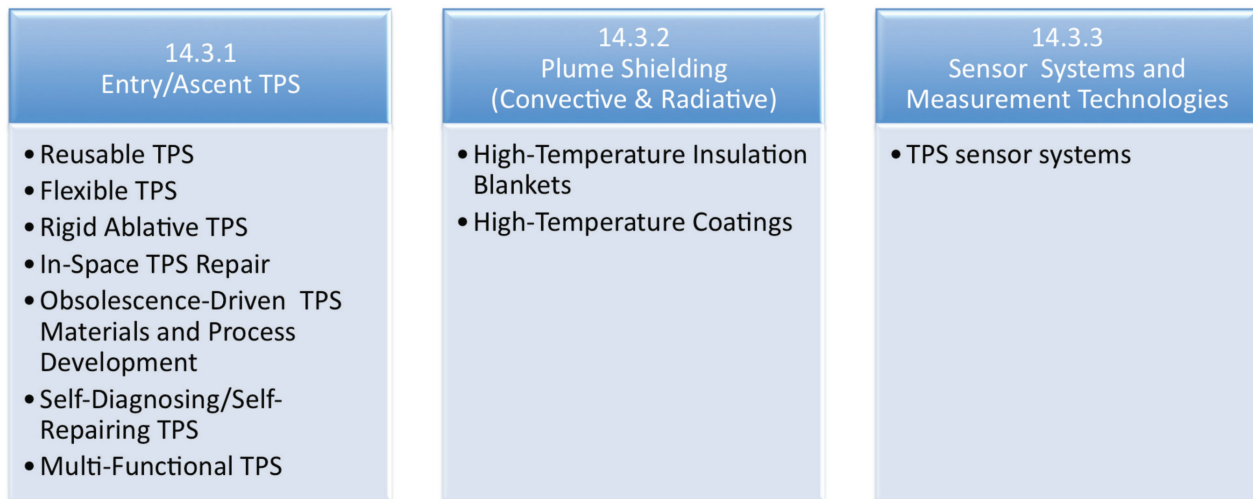


Figure 5. *Thermal Protection System TABS*

2.3.1.2. Flexible TPS (cross cutting with TA09-EDL)


System studies have shown that large heat shields provide a potentially enabling means to increase landed mass on the Martian surface. Large inflatable/flexible/deployable heat shields enable the consideration of a whole new class of missions. Flexible TPS is enabling for such deployable entry systems, and will provide strongly enhancing benefits for rigid systems as well (in terms of reduced life cycle cost and ease of manufacturing, as evidenced by Orbiter LCC data). The current operational SOA is the AFRSI blankets employed on the leeward side of the Orbiter, which are reusable systems designed for $\sim 5 \text{ W/cm}^2$ of maximum heating. Future deployable entry systems will require TPS concepts that can be stowed for months in space and then deployed into an entry configuration that can withstand $20\text{-}150 \text{ W/cm}^2$ of heating on Mars or Earth. These are envisioned as single or dual use systems, therefore multi-mission reusability will not be required. Both non-ablating and ablating concepts may be suitable, with the key trade being TPS development complexity versus system scalability and controllability. The current NASA portfolio includes small investments in $q < 50\text{-}75 \text{ W/cm}^2$ non-ablative materials (ARMD Hypersonics demonstration 2012), and $q < 150 \text{ W/cm}^2$ ablative materials (ESMD ETDD). All of these materials are low TRL at this time, although the first, an insulative 20 W/cm^2 multilayer system, is planned to be flight tested in 2012. Major technical challenges include maintaining thermal and structural properties after long duration storage in space, performance under aeroelastic and shear loading, and planetary protection re-

quirements for “soft goods.” Concept maturation to TRL 5 will require extensive ground testing, while maturation to TRL 6 may require a small-scale component level flight test. Development time estimated to be 5-6 years. Primary areas of recommended NASA investment include:

- Non-ablative (insulative or transpiration cooled) material concepts with high flexibility and stowability;
- Ablative material concepts, including systems that rigidize in-space or during entry. Includes high-heat flux semi-flexibles ($q > 150 \text{ W/cm}^2$) for low-cost application to rigid aeroshells (push technology);
- Multifunctional materials that provide MMOD/radiation protection and/or carry structural loads (push technology); and
- Improved thermal response and reliability quantification models.

2.3.1.3. Rigid Ablative TPS (cross cutting with TA09-EDL)

All NASA entry vehicles to date have employed rigid TPS, ranging from the reusable tiles on the Orbiter to ablative systems employed for planetary entry and Earth return from beyond LEO. For many exploration missions, such as near-Earth asteroid and Mars missions, ablative materials are an enabling technology and are needed for dual heat pulse reentries and for very high velocity entries (i.e., $> 11 \text{ km/s}$). However, the current selection of high TRL rigid TPS materials is inadequate for future mission objectives. TRL 6+ heatshield materials include PICA (Stardust, MSL), SLA-561V (MER, Phoenix), ACC (Genesis), Shuttle tiles (Orbiter), and RCC (Orbiter



WLE). Advances are required to significantly lower the areal mass of TPS concepts, demonstrate extreme environment capability, demonstrate high reliability, demonstrate improved manufacturing consistency and lower cost, and demonstrate dual-heat pulse (aerocapture plus entry) capability. Current agency investments include ablative materials development within ARMD (Hypersonics) and ESMD (Orion and ETDD), primarily in support of crewed return from the Moon and Exploration missions to Mars. It should be noted that Avcoat, while flown on Apollo and baselined for Orion, has not yet reached TRL 5 as a re-engineered concept. There is currently minimal investment in materials concepts for other mission classes and highly innovative multifunctional materials. Notably, missions that involve Earth return of crew from beyond the Moon, or robotic entry to Venus or the Giant Planets, have no available TPS solution at this time. Many other mission classes must resort to capable, but extremely heavy, TPS solutions. The addition of carbon nanotubes and nanofibers to strengthen the char layer promises the ability to reduce required ablator mass by up to 50 percent (See TA10 Section 3.2.1.5, and 3.2.1.6 for development timeframe). Recent efforts under Constellation have revived ablation analysis capabilities. These efforts should be expanded to include development of material response/flow field coupling codes (for both, engineering calculations and high-fidelity computational solutions), integration of ablation models into standard 3-dimensional thermal modeling codes, and ground testing to generate data for code correlation and validation. There is some TPS investment by other government agencies, but their primary focus is on reusable systems to support hypersonic cruise. Major technical challenges include the fidelity of current response models, availability of suitable ground test facilities, high uncertainties in input aerothermal environments (covered in Section 2.1.6) and the inherent conflict between low mass and robust performance. Concept maturation to TRL 5 will require extensive ground testing, while maturation to TRL 6 may require a small-scale component level flight test. Development time estimated to be 4-5 years for lower TRL concepts and 2-3 years for higher TRL concepts. Primary areas of recommended NASA investment include:

- Advanced Ablator materials
 - » Low- and Mid-density ablators for Earth return from beyond LEO and Mars entry missions, including dual heat pulse capable

materials with at least 40 percent lower areal mass than the current SOA (overlap with TA12).


- » Extreme environment ($q > 2 \text{ kW/cm}^2$, $p > 1 \text{ atm}$) materials, including redevelopment of extremely high-reliability Carbon-Phenolic for Mars Sample Return, and analog materials for future missions.
- Improved thermal response models, including high fidelity *ab initio* in-depth ablation/thermally-coupled response, gas-surface interactions, and computational materials design capability. (push technology, overlap with TA12)
- Improved processes for quantification of TPS margin and system reliability, including statistical analysis, testing techniques, and archival storage of agency thermal test data, as required for crewed vehicles and Mars/Europa sample return missions.

2.3.1.4. In-Space TPS Repair

A significant risk with spaceflight is damage to a vehicle due to MMOD impact. The Space Shuttle Orbiter on-orbit repair techniques activities should be continued to provide a repair capability for future spacecraft, both commercial and NASA-run. Assuming the development efforts leveraged off of methods developed for Space Shuttle Orbiter TPS repair such as the Tile Repair Ablator Dispenser (TRAD) and Reinforced Carbon-Carbon (RCC) crack repair, significant improvement in these techniques could be made with 2-3 years of effort. Repair techniques for significantly different TPS architectures, such as inflatable/deployable heat shields, will require longer development times.

2.3.1.5. Self-Diagnosing/Self Repairing TPS

One way to advance the TPS SOA is to study more advanced capabilities already displayed in nature – in this case, the ability to diagnose and heal itself. The self-diagnosing aspect of this would come from a health monitoring system (HMS) – an area that holds promise with recent advances in flight-worthy, quantitative fiber optic sensing, acoustic emission technology, wireless sensing, other full-field optical techniques, and other forms of non-destructive evaluation (NDE). The self-repairing aspect of this technology is not as mature but has seen some success in low TRL efforts. Advances in nanostructured materials (based on nanotubes and self-assembled materials) would enable both self-diagnoses as well as re-



pair. Development of some of the self-diagnosing technologies is likely in the 5 year range, but advancement of the self-repairing technology would probably require 10 - 20 years after advancements in design and manufacturing methods (see TA10 Section 3.2.1.2).

2.3.1.6. Multi-Functional TPS

Multidisciplinary approaches to traditional systems like TPS hold potential for enabling missions currently out-of-reach. The driving motivation behind this is, ultimately, the development of efficient spacecraft structures and systems. For example, spacecraft that are used for prolonged on-orbit periods (such as Orion) require robust MMOD protection. Structurally integrated TPS improves not only MMOD damage tolerance but also could provide significant weight savings as a load-bearing structure. This technology area includes TPS that is designed to be robust in the MMOD environment. Other multi-functional TPS, such as materials that also improve radiation protection, or combine cryogenic insulation with ascent/entry heating protection may also be included. The integration of TEGs into a TPS holds the potential to harvest free energy and save weight by reducing onboard power systems. Similarly, the development of TPS that could harvest ascent or plume heating for storage and later use (in space or on a planetary surface) would prove beneficial to several potential missions.. Development of these technologies is estimated to be a 5 - 10 year effort due to the low TRL level (2-3) with the TEG integrated TPS having a higher TRL level (4-5) and probably requiring less time to mature after recent successes.

2.3.1.7. Obsolescence-Driven TPS Materials and Process Development

This technology effort would ultimately provide TPS materials and processes that are directly applicable to heavy lift launch vehicles, commercial vehicles, space-based cryogenic propellant depots, and specialized ground-based test equipment requiring thermal insulation. This effort continues development of replacement cryoinsulation, primer, adhesive, and ablator TPS materials that are currently facing obsolescence. These four classes of materials are each subject to unique obsolescence issues that will limit their availability for future programs. The current generation of cryoinsulation materials are due to be phased out of production by 2015 and require replacement with more environmentally-compliant systems that provide no reduction in performance capabilities.

Ablative TPS, used to protect vehicles from higher heating environments, requires additional development to increase low-temperature substrate adhesion, reduce weight, and to identify replacement weatherproof coatings that have recently become commercially unavailable. TPS primer systems, used for both cryoinsulations and ablators, are designed to increase adhesion performance and maintain corrosion protection for spacecraft structures. Current primers are based on hexavalent chromium materials which continue to have reduced availability due to migration to more environmentally-friendly alternatives. Unfortunately, the materials developed by other government agencies are often incapable of meeting the more stringent spacecraft requirements. Adhesive materials, currently used for cryoinsulation applications, are mercury-based and in need of replacement to limit hazardous waste and ease processing restrictions. Based on lessons learned from the Ares I Upper Stage development work, additional activities have been linked to this task to increase effectiveness and reduce overall risk. These activities include development of a small-scale compounding/blending facility to directly support new material research and characterization, construction of a TPS tooling and cold storage facility, and development of advanced TPS testing techniques and capabilities to support the overall development effort. The time horizon for maturing these technologies is estimated to be 1-6 years depending on which material focus and supporting activities are chosen.

2.3.2. Plume Shielding (Convective and Radiative)

2.3.2.1. Plume Shielding

Protection of the spacecraft from the convective and radiative heating components of rocket engine and thruster plumes is required. It is believed that the Comet Nucleus Tour (Contour) spacecraft was lost due to the impingement of hot gases from an engine burn. Clearly, the physics of plume heating and impingement need to be better understood and techniques to analyze and design protection for the vehicle and its components from this heating are required. . This technology area includes high-temperature insulation blankets and coatings. Development time estimated to be 3 years.

2.3.3. Sensor Systems and Measurement Technologies

2.3.3.1. Sensor Systems and Measurement Technologies

Flight safety would be greatly improved with advances in ultra light-weight TPS sensor systems measuring temperature, strain, recession, flux, and other quantities of interest. This would be achieved by providing data needed for on-orbit/*in situ*, or self-repairing mechanisms, or to adaptive control algorithms that can compensate for damage without repair. Two sensor system technologies currently in development show great promise: FO, and wireless. Distributed FO sensor systems providing full-field data (strain, temperature) have been extensively ground tested, and have recently been successfully flight tested on aircraft, TRL 6-8. Current development efforts include redundant pathway FO networks that allow fiber failure without losing all downstream data (SOA TRL 3), ~5 years to TRL 6. Current SoA for high temperature RFID thermal sensors is TRL 2 for passive capability up to 500°C with TRL 6 expected with 5 years development. Higher temperature capability may be leveraged from current Air Force funded research. Other wireless sensors may be possible and may benefit from energy scavenging or increased energy density technology development efforts (see TA03).

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

The Thermal Management Systems TA does rely on collaboration and technology push from the TA10 (Nanotechnologies), TA11 (Modeling, Sim-

ulation, and Information Technology Systems) and TA12 (Materials, Structural & Mechanical Systems, and Manufacturing). Our technologies are then required as technology push or through collaborative development for the remaining eleven systems-based TA's. Specifically, for TA1 and TA13, advances in cryogenic tank and feedline joints insulation, helium conservation and/or elimination through the use of aerogels instead of active purge systems provide a significant impact to launch capability. Technologies developed in Cryogenic Systems will have direct impact on refueling operations for TA4, superconducting technologies for TA5, consumables, production and environmental protection for TA7, and cryocoolers required by TA8. In addition, technologies developed in Thermal Control Systems will have a direct impact on autonomous control and monitoring or robotic spacecraft developed by TA4, on the habitation and life support systems developed within TA6. Finally, technologies developed under Thermal Protection Systems have direct linkage to propulsion systems and instrumentation isolation and protection for TA9.

Interdependencies between the Thermal Management Systems TA and other TA's are highlighted in Figure 6.

4. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

The technologies identified in Section 2 will have spin-off potential to both the public and private sectors in applications or systems where control of the flow of heat is desired. A matrix representing what sectors the Thermal Management Systems technologies would be applicable and the

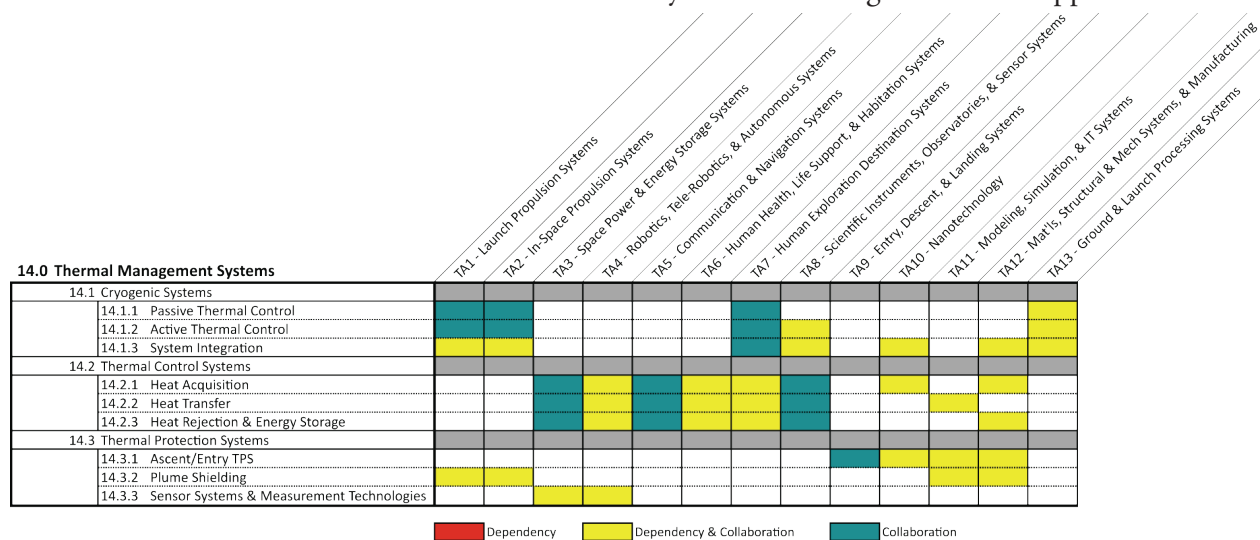


Figure 6. Thermal Management Systems TA Interdependencies

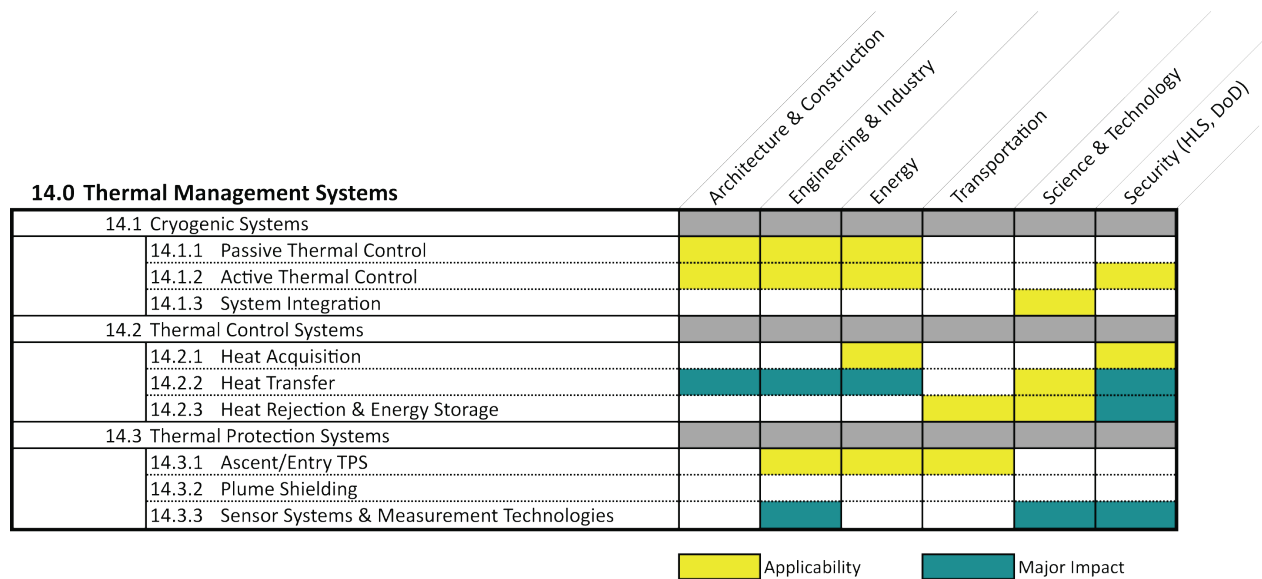


Figure 7. *Potential benefits of Thermal Management Systems technologies to other national needs*

estimated impact to that sector is provided in Figure 7.

Advances in space cryogenic thermal control systems have direct relevance to industry on Earth. Cryogenic processes are very energy intensive and greater system efficiencies will reduce power consumption and minimize product losses which will have a direct impact on the transportation, superconducting power transmission, biomedical, and remote sensing sectors. Technological advances in thermal control systems and in reducing thermal conductivity will have a significant impact on ground-based heating and cooling industries that would result in significant reductions in power consumption and operating costs.

The development of new thermal protection and hot structure systems may find application anywhere there are high heat loads or thermal gradients. Obvious benefits would be in the development of commercial spacecraft as well as military spacecraft and aircraft. Other applications may benefit reactors or other energy generation technologies where high heat dissipation is present. Additionally, any advancement in the multi-functional TPS could have strong spin-off potential. TEG technology could find broad application in furnace technology, automotive applications, reactors, and may have clean energy applications, as well. HMS applications are very broad and could be employed in commercial aircraft, the automotive industry, and a variety of structures. Lastly, the continued development of aerogels and other nano-structured materials would benefit, as they

already have, technologies centered on environmental protection or filtration systems.

5. NATIONAL RESEARCH COUNCIL REPORT

The earlier sections of this document were completed and issued publicly in December, 2010. NASA subsequently tasked the Aeronautics and Space Engineering Board of the National Research Council of the National Academies to perform the following tasks:

- **Criteria:** Establish a set of criteria to enable prioritization of technologies within each and among all of the technology areas that the NASA technology roadmaps should satisfy;
- **Technologies:** Consider technologies that address the needs of NASA's exploration systems, Earth and space science, and space operations mission areas, as well as those that contribute to critical national and commercial needs in space technology;
- **Integration:** Integrate the outputs to identify key common threads and issues and to summarize findings and recommendations; and
- **Prioritization:** Prioritize the highest-priority technologies from all 14 roadmaps.

In addition to a final report that addressed these tasks, NASA also tasked the NRC/ASEB with providing a brief interim report that "addresses high-level issues associated with the roadmaps, such as the advisability of modifying the number or technical focus of the draft NASA roadmaps."

In August, 2011, the NRC/ASEB delivered “An Interim Report on NASA’s Draft Space Technology Roadmaps” which, among other things, verified the adequacy of the fourteen Technology Areas as a top-level taxonomy, proposed changes in the technology area breakdown structure (TABS) within many of the TA’s, and addressed gaps in the draft roadmaps that go beyond the existing technology area breakdown structure.

On February, 1, 2012, the NRC/ASEB delivered the final report entitled “NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space”. The report prioritizes (e.g., high, medium, low) the technologies **within** each of the 14 Technology Areas, and also prioritizes **across** all 14 roadmaps [highest of the high technologies].

The remainder of this section summarizes:

- The changes that the NRC recommended to the TABS presented earlier in this document
- The NRC prioritization of the technologies in this TA, as well as highlights any of this TA’s technologies that the NRC ranked as a ‘highest of high’ technology.
- Salient comments and context, quoted verbatim, from the NRC report that provide important context for understanding their prioritization, findings, or recommendations.

5.1. NRC Recommended Revisions to the TABS

The NRC Panel recommended a minimal modification to the draft TA14 TABS: rename two of the original Level 3 technologies, namely “Integration and Modeling” to “Systems Integration” under TABS 14.1 “Cryogenic Systems” and renaming “Entry/Ascent TPS” to “Ascent/Entry TPS” under TABS 14.3 “Thermal Protection Systems”.

5.2. NRC Prioritization

The draft TA14 Roadmap is divided into nine Level 3 technologies which are organized by temperature regime – Cryogenic Systems, Thermal Control Systems, and Thermal Protection Systems. Table 1 lists the overall NRC Panel rankings for the nine TA14 Level 3 technologies, two of which they assessed as “high priority”. “Ascent/Entry TPS” received this designation based on their Quality Function Deployment (QFD) evaluation scores, which significantly exceeded the scores of the other technologies. “Active Thermal Control” was originally designated a “medi-

Table 1. NRC Prioritization of TA14 Level 3 Technologies


Section	Title	Priority
14.3.1	Ascent/Entry TPS	High
14.1.2	Active Thermal Control	High
14.2.3	Heat Rejection and Energy Storage	Medium
14.1.3	Systems Integration (Thermal Management)	Medium
14.1.1	Passive Thermal Control	Medium
14.3.3	Sensor Systems and Measurement Technologies (Thermal Management)	Medium
14.3.2	Plume Shielding (Convective and Radiative)	Medium
14.2.2	Heat Transfer	Low
14.2.1	Heat Acquisition	Low

um priority” upon completion of the QFD evaluation but was elevated to “high priority” since it is a needed technology to support zero boil off of cryogenic fluids.

5.3. Additional / Salient Comments from the NRC Reports

To place the priorities, findings, and recommendations in context for this TA, the following quotes from the NRC reports are noteworthy:

- “Effective heat shields and thermal insulation during ascent and atmospheric entry are mission-critical for all robotic and human missions that require entry into a planetary atmosphere.”
- “Ablative materials are enabling for all NASA, military and commercial missions that require high-mach number re-entry, such as near-Earth asteroid visits and Mars missions, whether human or robotic ...”
- “... level of effort for developing appropriate TPS is high, a joint NASA-industry development and testing program with careful coordination would maximize efficiency for NASA.”
- “Particularly critical level 4 technology items are Rigid Ablative TPS, Obsolescence-Driven TPS Materials and Process Development, Multi-Functional TPS, and Flexible TPS (cross-cutting with TA09-EDL and TA12).”
- “Low to zero boil off of cryogenic fluids will be mission-critical for long-duration missions, and cannot be achieved with present technology.”
- “Accelerate research on advanced active and passive systems to approach near-zero boil-off in long-term cryogenic storage.”
- Active Thermal Control: “NASA will be the de facto lead in guiding improvements in this technology because of the need for the



technology for long-term missions ...”

- “Radiators are used for energy removal from spacecraft and planetary base systems, and are mission-critical for many proposed missions. To reduce radiator mass, area, and pumping power, research is needed on variable emissivity, very low absorptivity-to-emissivity ratio, self-cleaning, and high-temperature coatings, as well as research on lightweight radiators or compact storage systems for extending EVA capability.”
- “Multifunctional systems can provide significant mass savings due to combining thermal and structural functions, allowing increased payload weight.”
- “Multi-functional TPS and multi-layer insulation (MLI) systems that combine thermal, structural, micrometeoroid and orbital debris (MMOD), and crew radiation protection could provide significant weight savings and enable long-duration missions, and can also be used for planetary habitat thermal and multifunctional protection.”
- “Upgrades to predictive codes for ablation during re-entry heating are needed to include closely coupled multi-phase ablation and radiative heating into the flow simulations, with careful attention given to verification, validation, and uncertainty quantification.”
- “Repair capability is especially important for long-duration missions, where no safe-haven repair facilities will be available.”
- “... re-entry thermal protection systems for high-velocity re-entry, radiation shielding, reduced mass structures, low-temperature cryogenic radiators, etc. will probably require either internal research teams or funding for contracted work.”

A specific finding in the NRC report addresses facilities; the following quote is specific to this TA.

- “Software validation and the use of ground test facilities are two overarching, cross-cutting issues pertinent to TA14 ...”
- “NASA maintains the test facilities necessary for qualifying new systems, but the test facilities must be modified to incorporate high radiative heat fluxes to simulate conditions expected for high-velocity re-entry.”

ACRONYMS

AC	Alternating Current
ADR	Adiabatic Demagnetization Refrigeration
AMPM	Agency Mission Planning Manifest
C/C	Carbon/Carbon
C/SiC	Carbon/Silicon Carbide
CPL	Capillary Pumped Loop
DC	Direct Current
DRA	Design Reference Architecture
DRM	Design Reference Mission
ECLSS	Environmental Control and Life Support System
EDL	Entry, Descent, and Landing
EVA	Extra Vehicular Activity
FO	Fiber Optic
HEFT	Human Exploration Framework Team
HMS	Health Monitoring System
IRVE	Inflatable Reentry Vehicle Experiment
ISRU	In Situ Resource Utilization
ISS	International Space Station
JT	Joule-Thompson
JWST	James Webb Space Telescope
LEO	Low Earth Orbit
LHP	Loop Heat Pipe
MLI	Multi Layer Insulation
MMOD	Micro Meteoroid and Orbital Debris
NDE	Nondestructive Evaluation
PCM	Phase Change Material
RCC	Reinforced Carbon-Carbon
RFID	Radio Frequency Identification
RTV	Room Temperature Vulcanizing elastomer
SHReD	Supplemental Heat Rejection Device
SOA	State of the Art
SOMD	Space Operations Mission Directorate
TA	Technology Area
TABS	Technology Area Breakdown Structure
TASR	Technology Area Strategic Roadmap
TCS	Thermal Control System
TEC	Thermal Electric Cooler
TEG	Thermo-Electric Generator
TPS	Thermal Protection Systems
TRAD	Tile Repair Ablator Dispenser
TRL	Technology Readiness Level
UHTC	Ultra High Temperature Ceramic
ZBO	Zero Boil Off

ACKNOWLEDGEMENTS

The draft NASA technology area roadmaps were developed with the support and guidance from the Office of the Chief Technologist. In addition to the primary author's, major contributors for the TA14 roadmap included: the OCT TA14 Roadmapping POCs, Tibor Balint and Tammy Gafka; the NASA Center Chief Technologist and NASA Mission Directorate reviewers, and the following individuals Ryan Stephan, Stan Bouslog, Eric Hurlbert, and the Multi-Center Cryogenic Fluid Management Team.



April 2012

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